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United States Patent Application for

A

Method and Apparatus for a

Quadrupole Transmitter for

Directionally Sensitive Induction Tool

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Cross Reference to Related Applications

[0001] The patent application claims priority from U.S. Patent Application 10/338,871 filed on March 14, 2003 entitled "A Method and Apparatus for a Quadrupole Transmitter for Directionally Sensitive Induction Tool" by G. Itskovich, A. Besspalov and B. Chakarov.

5 Background of the Invention

Field of the Invention

[0002] The present invention pertains to the field of performing resistivity measurements for the purpose of geo-steering in two operational modes. A directional mode provides sensitivity of the received signals to the azimuthal characteristics of the formation and a deep mode provides large
10 depth of investigation for resistivity determination and bed boundary detection relative to the borehole and tool.

Summary of the Related Art

[0003] Electromagnetic induction and wave propagation logging tools are commonly used for determination of electrical properties of formations surrounding a borehole. These logging tools
15 give measurements of apparent resistivity (or conductivity) of the formation that, when properly interpreted, reasonably determine the petrophysical properties of the formation and the fluids therein.

[0004] The physical principles of electromagnetic induction resistivity well logging are described, for example, in H.G. Doll, *Introduction to Induction Logging and Application to Logging of Wells Drilled with Oil-Based Mud*, Journal of Petroleum Technology, vol. 1, p.148, Society of Petroleum Engineers, Richardson, Tex. (1949). Many improvements and modifications to

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electromagnetic induction resistivity instruments have been devised since publication of the Doll reference, *supra*. Examples of such modifications and improvements can be found, for example, in U.S. Pat. No. 4,837,517; U.S. Pat. No. 5,157,605 issued to *Chandler et al.*; and U.S. Pat. No. 5,452,761 issued to *Beard et al.*

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[0005] A typical electrical resistivity-measuring instrument is an electromagnetic induction military well logging instrument such as described in U.S. Pat. No. 5,452,761 issued to *Beard et al.*

The induction logging instrument described in the *Beard* '761 patent includes a number of receiver coils spaced at various axial distances from a transmitter coil. Alternating current is

10 passed through the transmitter coil, which induces alternating electromagnetic fields in the earth formations. Voltages, or measurements, are induced in the receiver coils as a result of electromagnetic induction phenomena related to the alternating electromagnetic fields. A continuous record of the voltages form curves, which are also referred to as induction logs. The induction instruments that are composed of multiple sets of receiver coils are referred to as multi-array induction instruments. Every set of receiver coils together with the transmitter is named as a subarray. Hence, a multi-array induction consists of numerous subarrays and acquires measurements with all the subarrays.

[0006] Voltages induced in the axially more distal receiver coils are the result of electromagnetic induction phenomena occurring in a larger volume surrounding the instrument, and the voltages induced in the axially proximal receiver coils are the result of induction phenomena occurring more proximal to the instrument. Therefore, different receiver coils see a formation layer bound-

ary with different shoulder-bed contributions, or shoulder-bed effects. The longer-spaced receiver coils see the formation layer boundary at further distance from the boundary than the shorter-spaced receiver coils do. As a result, the logs of longer-spaced receiver coils have longer shoulder-bed effects than the logs of shorter-spaced receiver coils.

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[0007] If the layers are not perpendicular to the axis of the instrument, the conductivity of the media surrounding the instrument can vary azimuthally, causing the inferences about the conductivity from the measurements of the induction voltage to be in error. A method for correcting the error is described in U.S. Pat. No. 5,774,360 issued to Xiao and Zhou. The method requires the
10 relative dip angle as a priori information. The relative dip angle is the angle between the borehole axis and the normal of the bedding plane. Because the formation layers can also be inclined, the relative dip angle is normally unknown even though the wellbore deviation is known. U.S. Pat. No. 6,049,209 issued to Xiao and Geldmacher teaches another method has also been developed to interpret induction logs in the environments of relative inclination and anisotropy. The
15 method requires the relative dip angle and the anisotropy coefficient as a priori information. The anisotropy coefficient can be defined as the ratio between the resistivity perpendicular to bedding and the resistivity parallel to bedding.

[0008] A limitation to the electromagnetic induction resistivity well logging instruments known
20 in the art is that they typically include transmitter coils and receiver coils wound so that the magnetic moments of these coils are substantially parallel only to the axis of the instrument. Eddy currents are induced in the earth formations from the magnetic field generated by the transmitter

coil, and in the induction instruments known in the art. These eddy currents tend to flow in ground loops which are substantially perpendicular to the axis of the instrument. Voltages are then induced in the receiver coils related to the magnitude of the eddy currents. Certain earth formations, however, consist of thin layers of electrically conductive materials interleaved with thin layers of substantially non-conductive material. The response of the typical electromagnetic induction resistivity well logging instrument will be largely dependent on the conductivity of the conductive layers when the layers are substantially parallel to the flow path of the eddy currents. The substantially non-conductive layers will contribute only a small amount to the overall response of the instrument and therefore their presence will typically be masked by the presence of the conductive layers. The non-conductive layers, however are those layers which are typically hydrocarbon-bearing and are of the most interest to the instrument user. Some earth formations which might be of commercial interest therefore may be overlooked by interpreting a well log made using the electromagnetic induction resistivity well logging instruments known in the art.

[0009] United States Patent 5,999,883 issued to *Gupta et al.*, (the “Gupta patent”), the contents of which are fully incorporated herein by reference, discloses a method for determining the horizontal and vertical conductivity of anisotropic earth formations. Measurements are made of electromagnetic induction signals induced by induction transmitters oriented along three mutually orthogonal axes. One of the mutually orthogonal axes is substantially parallel to a logging instrument axis. The electromagnetic induction signals are measured using first receivers each having a magnetic moment parallel to one of the orthogonal axes and using second receivers each having a magnetic moment perpendicular to one of the orthogonal axes, which is also perpen-

dicular to the instrument axis. A relative angle of rotation of the perpendicular one of the orthogonal axes is calculated from the receiver signals measured perpendicular to the instrument axis. An intermediate measurement tensor is calculated by rotating magnitudes of the receiver signals through a negative of the angle of rotation. A relative angle of inclination of one of the orthogonal axes, which is parallel to the axis of the instrument is calculated, from the rotated magnitudes, with respect to the direction of the vertical conductivity. The rotated magnitudes are rotated through a negative of the angle of inclination. Horizontal conductivity is calculated from the magnitudes of the receiver signals after the second step of rotation. An anisotropy parameter is calculated from the receiver signal magnitudes after the second step of rotation. Vertical conductivity is calculated from the horizontal conductivity and the anisotropy parameter.

[0010] The relative formation dip angle is vital for proper and accurate interpretation of data acquired by the new multi-component induction instrument. This newly developed induction instrument comprises three mutually orthogonal transmitter-receiver arrays. These configurations allow determination of both horizontal and vertical resistivities for an anisotropic formation in vertical, deviated, and horizontal boreholes. A description of the tool can be found in WO 98/00733, *Electrical logging of a laminated formation*, by Beard et al (1998). The transmitters induce currents in all three spatial directions and the receivers measure the corresponding magnetic fields (H_{xx} , H_{yy} , and H_{zz}). In this nomenclature of the field responses, the first index indicates the direction of the transmitter, the second index denotes the receiver direction. As an example, H_{zz} is the magnetic field induced by a z-direction transmitter coil and measured by a z-

directed receiver. The z-direction is parallel to the borehole. In addition, the instrument measures all other cross-components of the magnetic fields, i.e., H_{xy} , H_{xz} , H_{yx} , H_{yz} , H_{zx} , and H_{zy} .

[0011] The signals acquired by the main receiver coils (H_{xx} , H_{yy} , and H_{zz}) are used to determine both the horizontal and vertical resistivity of the formation. This is done by inverse processing techniques of the data. These inverse processing techniques automatically adjust formation parameters in order to optimize in a least-square sense the data match of the synthetic tool responses with measured data. Required inputs in this process are accurate information of the relative formation dip and relative formation azimuth. This information can be derived using in addition to the main signals (H_{xx} , H_{yy} , and H_{zz}) the data from the cross-components.

[0012] Conventional induction tools comprising only coaxial transmitter-receiver coil configurations do not have azimuthal sensitivity. Therefore, in a horizontal wellbore, the data do not contain information about directionality of the formation. It is not possible to distinguish whether a layer is above or below the borehole from these data alone. There is a need to be able to determine directionality of the formation.

Summary of the Invention

[0013] The new quadrupole system of the present invention in combination with MPR enables MWD resistivity measurements with azimuthally sensitivity. The system consists of a dual loop transmitter and one coil receiver placed between transmitting coils. The moments of the transmitting and receiving coils are substantially perpendicular to the borehole axis. The optimal length of the system is (about) 1 m. In order to provide large depth of investigation the quadrupole system is preferably combined with existing MPR tools. The present invention provides a quadrupole system with azimuthal resolution in the directional mode and a MPR high depth of investigation in the deep resolution mode. To reduce ambiguity due to zero crossings in the data multi-frequency measurements as well as the measurements of both in-phase and quadrature components are performed.

[0014] The present invention provides a method and apparatus for performing resistivity measurements for the purpose of geo-steering with 180 degree azimuthal resolution. All the measurements represent a complementary set of data acquired in two operational modes. The directional mode providing sensitivity of the received signals to the azimuthal characteristics of the formation. The deep mode providing large depth of investigation for resistivity (R_t) determination and bed boundary detection. The directional mode can be implemented using one receiving coil placed in between quadruple type transmitter. The whole module is about 1m in length while quadruple coils comprising transmitter are separated by about 10 cm distance. In another embodiment the deep mode represents an improvement over conventional multiple propagation re-

sisitivity (MPR) measurements that provide a depth of investigation for resistivity determination and bed boundary detection.

[0015] Preferably, both directional and deep measurement modes are combined in one single

5 tool. The tool comprises at least two transmitter coils (a quadruple transmitter) and an array of transversal coils in the receiver portion of the tool. The moments of the transmitting and receiving coils are perpendicular to the borehole axis. The transmitter provides a switch to switch polarity of the current in each of the transmitter coils. Several receiving coils are placed at the different distances from the quadruple transmitter, for example 1 meter between receiving coils. The pre-
10 sent invention provides a resistivity tool that acquires data at several operating frequencies in the range of 100 kHz to 2 MHz. The preferred tool provides a controller and control program that performs switching polarity of the current in the transmitter coils so that the data of both directional and deep mode can be acquired. The deep mode data are acquired when magnetic mo-
15 ments of two transmitting loops are switched so that the moments point in the same direction and the directional mode data are acquired when the moments point in opposite directions. The opposing moments in the directional mode also reduce eddy currents induced in the conductive drill or tool.

Brief Description of the Figures

[0016] The novel features of this invention, as well as the invention itself, will be best understood from the attached drawings, taken along with the following description, in which similar reference characters refer to similar parts, and in which:

5 **Fig. 1a and Fig 1b** illustrate a two-layered formation models with up and down boundary respectively;

Fig. 2 illustrates how dipole-dipole measurements cannot distinguish between models with up and down boundaries as neither quadrature nor in-phase components change as the boundary position is changed;

10 **Fig. 3** illustrates a quadrupole transmitter with two similar coils having magnetic moments oriented in opposite direction are used introduce uniqueness in signals from a boundary above and below the tool. The moments of the transmitting and receiving coils are perpendicular to the borehole axis;

Fig. 4 illustrates a quadrupole transmitter with receiver coil placed in between transmitting coils to differentiate between models with up and down boundaries with a sign reversal generated in both in-phase and quadrature components;

15 **Fig. 5** illustrates a dependency of the receiving signal on spacing S between quadrupole transmitter and dipole receiver;

Fig. 6 illustrates that the signal to noise ratio (SNR) is not sensitive to the coil length as a
20 +/- 50% deviation from the optimal length results in only a 5% loss of SNR compared to maximum level;

Fig. 7 illustrates mathematical modeling results for a two-layered formation performed at three frequencies- 100 kHz, 400 kHz, 2 MHz;

Fig. 8 illustrates the quadrature component depth of investigation of 0.6, 2.0, 2.3 m for 100 kHz, 400 kHz and 2 MHz correspondingly;

Fig. 9 illustrates a magnetic field measured for a Z-transmitter and an X-receiver in a three-layer formation;

Fig. 10 illustrates that the magnetic field (imaginary part) changes sign as the tools moves from the upper layer boundary toward the lower boundary layer;

Fig. 11 and **Fig. 12** illustrate modeling results of in-phase (**Fig. 11**) and quadrature (**Fig. 12**) components for quadrupole and cross-component arrangements;

Fig. 13 and **Fig. 14** illustrate modeling results of in-phase (**Fig. 13**) and quadrature (**Fig. 14**) components for quadrupole and cross-component arrangements;

Fig. 15 illustrates an alternative embodiment with a transmitter switched into the directional mode switching configuration; and

Fig. 16 illustrates an alternative embodiment with a transmitter switch into the deep mode switching configuration. The moments of the transmitting and receiving coils are perpendicular to the borehole axis.

Detailed Description of a Preferred Embodiment

[0017] The present invention provides a method and apparatus for performing resistivity measurements with azimuthal resolution. The present invention provides for larger depth of investigation for resistivity (R_t) determination and bed boundary detection during reservoir navigation along with enhanced accuracy over a broad range of resistivities. The present invention provides MPR with resolving capability in azimuthal direction that leads to a increased and more effective usage of MPR for geo-steering.

[0018] Turning now to **Fig.1**, **Fig. 1** illustrates a two-layered formation models with up/down boundary **102**. Resistivities of the layers **106**, **104**, are $\rho_1 = 10$ ohm-m and $\rho_2 = 1$ ohm-m respectively. The excitation dipole **108** is oriented in the same direction as receiving dipole **110**. The tool (not shown) is placed at a different distance L , containing dipoles **108**, **110** from the boundary **102** inside the resistive layer. The tool traverses a bore hole **930** considered to be horizontal and parallel to layer boundaries **102**. The dipole-dipole measurements cannot distinguish between models with up and down boundaries. The present invention provides a quadrupole transmitter with azimuthal resolution.

[0019] **Fig. 1a** and **Fig. 1b** illustrate a two-layered formation with resistivities $\rho_1 = 10$ ohm-m and $\rho_2 = 1$ ohm-m and traditional ZZ dipole-dipole arrangement (ZZ refers to excitation dipole oriented in Z direction and receiving dipole oriented in the same Z direction). The tool is placed at a different distance L from the boundary inside the resistive layer The tool is traveling within a horizontal well (not shown) which is parallel to layer boundaries. In this situation ZZ dipole-

dipole measurements can not distinguish between boundary positioning arrangements presented in **Fig. 1a** and **Fig. 1b**.

[0020] **Fig.2.** illustrates how dipole-dipole measurements can not distinguish between models with up and down boundaries – neither quadrature **202** nor in-phase **204** components do not change as the boundary position is changed between above the tool (**Fig. 1a**) and below the tool (**Fig. 1b**). The situation is not any different if the moments of both transmitting and receiving coils are oriented like in the X direction (parallel to the bore hole and boundary layers) as the measurements still cannot distinguish between boundary positioning presented in **Fig. 1a** and **Fig. 1b**.

[0021] To introduce uniqueness between the measurements of the boundary positioning arrangement shown in **Fig. 1a** and the boundary positioning arrangement shown in **Fig. 1b**, the present invention provides a quadrupole transmitter instead of a of dipole transmitter. **Fig. 3** illustrates a preferred quadrupole transmitter **300** with two similar transmitter coils **302**, **304** having magnetic moments oriented in opposite direction are used to introduce a sign change in readings between **Fig. 1a** and **Fig. 1b**. A receiver coil **306** is placed between transmitter coils **302** and **304**. Coils **302**, **304** are separated by spacing $d = 10$ cm. The moments of the transmitting coils **302**, **304** and receiving **306** coil are substantially perpendicular to the borehole **930** longitudinal axis. **Fig. 4** illustrates measurements made using a quadrupole transmitter with receiver coil placed in between transmitting coils with opposite polarity moments to differentiate models

with up and down boundaries. A sign reversal is observed in both in-phase and quadrature components.

[0022] The quadrupole transmitter provides two similar transmitter coils **302**, **304** which have magnetic moments oriented in opposite direction as shown in **Fig. 3**. The coils **302**, **304** are separated by spacing d (in the present example of a preferred embodiment, the calculations use $d=10$ cm). As shown in **Fig. 4** quadrupole transmitter **300** with receiver coil **306** placed in between transmitting coils **302**, **304** enables the present invention to differentiate between the models shown in **Fig. 1a** and **Fig. 1b**. Note that the sign reversal is present in both the in-phase **404** and quadrature **402** components an “up “ boundary (above the tool) and the “ down” boundary (below the tool) in-phase **406** and quadrature **408** components.

[0023] In an alternative embodiment, the reciprocal arrangement is provided when one transmitting coil and quadrupole receiver operate in two modes having opposite orientations of the receiving moments in the directional mode and the coincide orientations in the deep mode.

[0024] **Fig. 5** illustrates modeling results, which show a dependency of the receiving signal on spacing S (meters) between quadrupole transmitter and dipole receiver. The distance L from transmitter to the boundary is fixed and spacing S is varied. The signal **502** is a smooth function of the spacing and does not drop very fast with a spacing increase. **Fig. 5** illustrates mathematical modeling results illustrating dependency of the receiving signal on a spacing S between a quadrupole transmitter and a dipole receiver. In **Fig. 5**, the distance L from transmitter to the boundary is fixed and spacing S varies. **Fig. 5** shows that the amplitude of the signal **502** is a

smooth function of the spacing and does not drop very fast with a spacing S increase. **Fig. 5** illustrates that increasing the length of the coil increases the measured signal. At the same time the noise in the receiving antenna is proportional to \sqrt{D} where D is the optimal antenna size. If the length of the antenna exceeds the optimal size D the benefits of the signal increase will be over-
 5 compensated by the large noise level. The optimal coil length is defined as that coil length which provides a maximum of the signal/noise ratio (SNR). Preferably, the maximum of the SNR is defined as

$$SNR = \frac{\int_0^L \dot{B} dr}{\sqrt{L}}$$

10 where \dot{B} is the induced magnetic field along the path of integration.

[0025] As shown in **Fig. 6**, the SNR **602** is not overly sensitive to the coil length as a +/- 50% deviation from the optimal coil length leads to only 5% loss of SNR compared to maximal level.

The estimate of the optimal receiver coil length is for the very short quadrupole transmitter.

15 Since receiver and transmitter characteristics are reciprocal this estimate is also valid for the finite transmitter size. For the purpose of geo-steering the short module consisting of three 1m long coils with the central coil used as a receiver and two others as a quadrupole transmitter is optimal.

[0026] Fig. 6 illustrates the results of the integration. The signal as shown in Fig. 6 has been normalized to the maximal value corresponding to 1m-coil length. As we can see from Fig. 6 the SNR is substantially insensitive to a coil length. A +/- 50% deviation from the optimal length leads to only 5% loss of SNR compared to maximal level. This estimate of the optimal receiver coil length was performed for the very short quadrupole transmitter. Since receiver and transmitter are reciprocal this estimate is also valid for the finite transmitter size as well. Thus, for the purposes of geo-steering, the short module consisting of three 1m long coils can be used with the central coil used as a receiver and two others as a quadrupole transmitter.

[0027] Fig. 7 illustrates mathematical modeling results for a two-layered formation performed for the three frequencies- 100 kHz 706, 400 kHz 704, 2 MHz 702. All the parameters in the model are fixed except distance to the boundary. The moment of both receiving and transmitting loops are $3.5E-03 \text{ m}^2$. The distance between coils comprising the quadrupole is 10 cm. Each transmitting coil has 8 turns. In a preferred embodiment, the current strength is 0.64 amp. As shown in Fig. 7 and Fig. 8, frequency dependence of quadrature (Fig. 8) and in-phase (Fig. 7) components are illustrated. A threshold 708 is indicated on the plot, which corresponds to a minimal detectable signal of 20 nV, the signal that can be reliably distinguished from the noise in a preferred embodiment. As shown in Fig. 7, for the in-phase component the maximum depth of investigation achievable with 100 kHz is 1 m 710, while for the 400 kHz and 2 MHz it is 1.4 m 712 and 2.2 m 714 correspondingly.

[0028] Fig. 8 illustrates that in the case of the quadrature component, the depth of investigation is 0.6 **810**, 2.0 **812**, 2.3 m **814** for 100 kHz **806**, 400 kHz **804** and 2 MHz **802** correspondingly.

The modeling data show that both in-phase and quadrature component have zero crossings.

Thus, the present invention performs measurements at different frequencies to reliably interpret

5 the data and reduce the ambiguity associated with zero crossings.

[0029] Directional resistivity may be measured using cross-component coils. One important cross-component combination is a coaxial (Z) transmitter and an orthogonal (X) receiver. Such a combination has the capability of distinguishing targets located above or below, provided that the
10 targets are within the depth of investigation of the device. This directional resistivity capability enables determination of which way the drill bit is approaching the geologic target, that is, whether the geological target is above or below the resistivity tool.

[0030] To illustrate of the directionality of cross-component measurement, **Figure 9** shows the
15 magnetic field measured for a Z-transmitter **916** and an X-receiver **914** in a three-layer formation **909**. The tool **910** is shown traversing a highly deviated borehole **930** drilled into the formation **909**. The upper **912** and lower **920** layers are 1 ohm-m and the middle **918** layer in which the tool **910** resides is 10 ohm-m. The transmitter **916** and receiver **914** are aligned such that the tool axis is parallel to the bed boundaries **905** and **907**.

20 [0031] As shown in **Fig. 10**, observe that the magnetic field (imaginary part) changes sign as the tools moves away from the upper layer boundary **907**, between upper layer **912** and middle layer

918 towards the lower boundary 905 between lower layer 920 and middle layer 918. This sign change provides information for distinguishing between approaching layers that are above the tool (such as upper layer 912 in Fig. 9) from layers that are below the tool (such as lower layer 920 in Fig. 9).

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[0032] Fig. 11 and Fig. 12 illustrate modeling results of in-phase (Fig. 11) and quadrature (Fig. 12) components for quadrupole and cross-component arrangements. The absolute value of the signal was calculated for the 400 kHz frequency. In the case of cross-component arrangement, a 91-cm spacing between the receiver and transmitter was used. At a frequency of 400 kHz the cross-component measurements provide 20% larger depth of investigation.

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[0033] In the case illustrated in Fig. 11 and Fig 12, the dipole-transmitting coil oriented along Y-direction is used as a transmitter and Z-oriented dipole is provided as a receiver. Mathematical modeling results for both quadrupole and cross-component arrangements are presented in Fig. 11 and Fig 12. Again, two-layered formation model was used and boundary position was varied. As shown in Fig. 11 and Fig. 12, the plots at frequency of 400 kHz of the cross-component measurements provide a 20% increase in the depth of investigation. As the frequency is increased the situation is dynamic.

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[0034] Fig.13 and Fig. 14 illustrate modeling results of the in-phase (Fig. 13) and the quadrature (Fig. 14) components for quadrupole and cross-component arrangements. At a frequency 2 MHz the quadrupole transmitter provides a higher signal level for the shallow depth investigation (0-70

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cm) while cross-component arrangement is superior if the higher depth of investigation (0.7–2) m is required. At frequency 2 MHz the cross-component measurements have only 10% larger depth of investigation compared to quadrupole arrangement.

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[0035] In an alternative embodiment, another arrangement comprising an array induction tool comprising a dual loop transmitter and an array of receiving coils is provided. The transmitter is provided a polarity switch for switching polarity of the current in each of the two loops. Magnetic moments of the transmitting loops **1502**, **1504** are oriented perpendicular to a longitudinal borehole axis. Several receiving coils **1506** oriented along the same direction are placed at the distances of approximately 1 meter apart. The resistivity tool of the present invention acquires data at several operating frequencies in the range of 100 kHz to 2 MHz. By switching polarity of the current in the transmitter the data of both directional and deep mode may be acquired, the directional mode when the moments are in the opposite directions (**Fig. 15**) and the deep mode when magnetic moments of two transmitting loops have coincide directions (**Fig. 16**).

[0036] In another embodiment of the present invention, the method of the present invention is implemented as a set computer executable of instructions on a computer readable medium, comprising ROM, RAM, CD ROM, Flash or any other computer readable medium, now known or unknown that when executed cause a computer to implement the method of the present invention.

[0037] While the foregoing disclosure is directed to the preferred embodiments of the invention various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope of the appended claims be embraced by the foregoing disclosure. Examples of the more important features of the invention have been summarized rather broadly in order that
5 the detailed description thereof that follows may be better understood, and in order that the contributions to the art may be appreciated. There are, of course, additional features of the invention that will be described hereinafter and which will form the subject of the claims appended hereto.